

Simulation of the magnetic and thermal characteristics of MnZn and NiZn AC dipoles for the Mu2e experiment

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Introduction

Mu2e experiment provides the ability to find charged lepton flavor violation with an unprecedented sensitivity of 6×10^{-17} at a 90% confidence level. Such sensitivity is achieved due to usage of strong alternating magnetic field able to clean-up time-space between protons bunches to the level of 10^{-6} . The experiment details can be found in Mu2e proposal [1].

The main idea of clean-up technique is to synchronize alternating magnetic field with proton beam, so that particles in bunches are conserved and particles in gaps are driven away. The basic scheme of clean-up technique is shown on Figure 1.

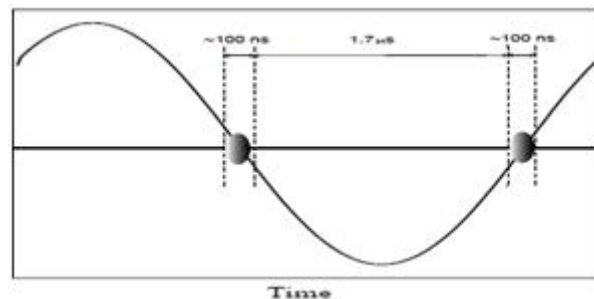


Figure 1 Clean-up technique

The clean-up block scheme is shown on Figure 2. Two AC dipole magnets are used to clean-up the beam. In MnZn AC dipole magnet ~ 180 G 300 kHz alternating magnetic field is created. NiZn magnet operates on 5.1 MHz (17th harmonic to carrying frequency) and creates 9 G field. The combined operation of two magnets creates alternating magnetic field with flatten zones in nodes (Figure 3). Flatten zones allow to decrease particles losses from bunches [2].

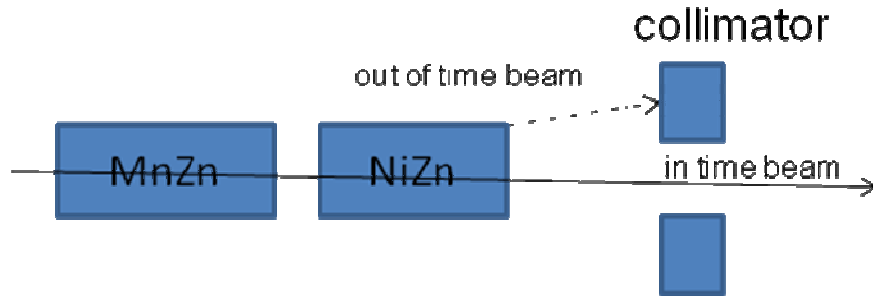


Figure 2 Experiment scheme

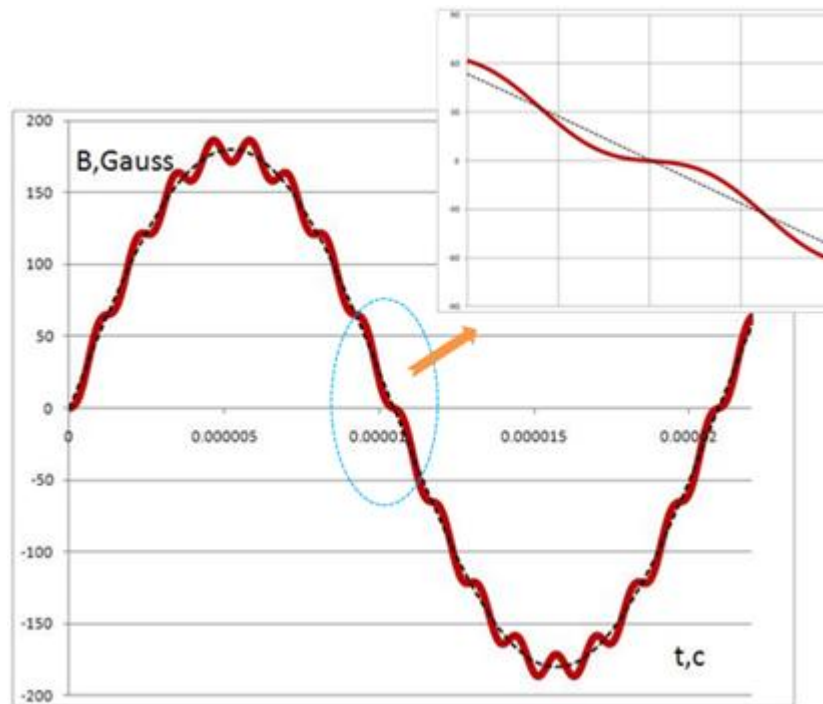


Figure 3 combined magnetic field

Each of the dipole magnets consists of several dozen ferrite plates operating in vacuum. Ferrite samples have high permeability and can be used to create strong alternating magnetic field. The main drawback of ferrite materials usage is possible overheating. Both BH-loss and eddy current loss can cause changing of the material properties and decreasing of the magnetic flux. Several experiments on MnZn and NiZn ferrites were launched to determine whether these materials can be used in the magnets. The MN60LL was chosen as a MnZn ferrite material, due to its high permeability and low hysteresis loss. The CMD10 was chosen as NiZn ferrite material, because it has highest saturation among NiZn ferrites, along with medium permeability and high resistivity.

For material properties studies ferrite plate (Figure 4) were created. A copper tube with room temperature water and aluminum were used for additional heat dissipation. Several resistance temperature detectors (RTDs) are placed on the plate surface.

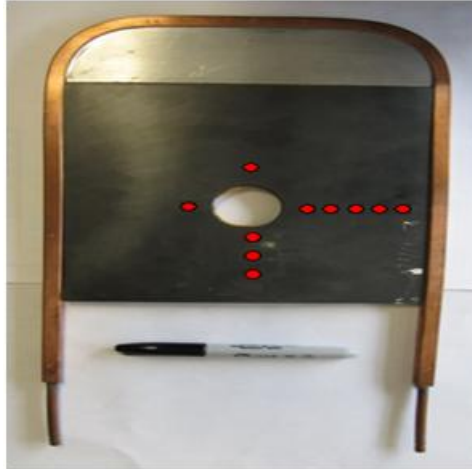


Figure 4 Ferrite plate

For both MnZn and NiZn materials the required magnetic field was achieved. The heat losses were about 50W and the surface temperature was less than 80 C. Though the results are optimistic some improvements should be done to decrease energy loss to minimum. Moreover, it has to be encountered that m2e experiment conditions are more severe, so the ferrite plates heating will be higher due to the lower heat dissipation in vacuum.

The task is to optimize the ferrite plate so that to decrease heat loss. Different parts of system can be optimized:

1. Cooling system
2. Plate geometry
3. Material

In fact, analytical calculations of each optimization effect are complicated. So physics simulation can be used to find appropriate decision. Moreover simulation can provide theoretical model to check the experiments reliability.

Simulation principles

Simulation is done using engineering modeling software ANSYS. Low-frequency electromagnetic analysis uses Maxwell's equations as the basis of field analysis. The primary degrees of freedom that the finite element solution calculates are magnetic and electric potentials. Other magnetic field quantities such as magnetic flux, losses are derived from these degrees of freedom. Eddy current loss is supposed to be calculated using theoretical formulation:

$P_e = c \cdot B_m^2 \cdot f^2 \cdot d^2 / p$, where c is constant depending on geometry of the sample, B_m – maximum induction, f – frequency, d – smallest dimension transverse to flux, p – resistivity, ohm*cm.

The basis of thermal analysis for ANSYS is a heat balance equation obtained from the principal of conservation of energy. The finite element solution performed via ANSYS calculates nodal temperatures, and then uses it to obtain thermal quantities (thermal distribution, thermal flux).

Only a half symmetry part of plate is considered for the analysis. Ferrite plate and wire are shown on Figure 5. The wire and the plate are enclosed in an air box of size 0.6 x 0.8 x 0.7 m. Flux parallel boundary conditions are imposed on the exterior surface of the air enclosure.

Ferrite plate geometrical parameters:

Px = 0.1 (half length, m)
Py = 0.2 (height, m)
Cy = 0.11 (hole center position(y), m)
Rc = 0.02 (hole radius, m)
Pz = 0.01 (plate thickness, m)

Wire geometrical parameters:

Rw = 0.001 (wire radius, m)
Wl = 0.3 (wire length, m)

Air, wire and plate are modeled using SOLID237 element type. This element is a 3-D 10-node, capable of modeling electromagnetic fields. Nonlinear magnetic B-H properties can be set and eddy currents can be calculated for this element type. Both the wire and the ferrite plate are modeled using the electromagnetic analysis option (KEYOPT(1) = 1). In addition, KEYOPT(5) is set to 1 for the wire to suppress the eddy currents. The air box is modeled using the magnetic analysis option KEYOPT(1) = 0. Wire electrical conductivity was set to $2e-8 \text{ ohm} \cdot \text{m}$.

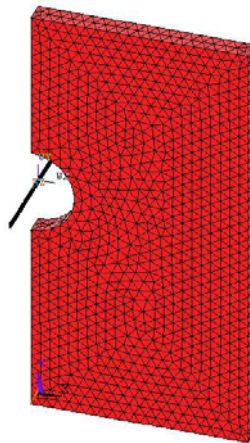


Figure 5 Ferrite plate and wire

A harmonic electromagnetic analysis is performed to determine the field distribution and eddy current loss in a ferromagnetic plate. The electromagnetic analysis is followed by a steady-state thermal analysis to determine the temperature distribution in the plate due to Joule heating produced by the eddy currents. SOLID87 element type is used for temperature distribution calculations in ferrite plate.

Simulation results

Simulation has shown that magnetic flux trajectories are closed to circles (Figure 6). Different colors represent different magnetic flux value. Figure 7 shows magnetic flux lines direction in the closed to hole area. Eddy current distribution is calculated (Figure 8, 9). Currents are directed radial in polar coordinate system.

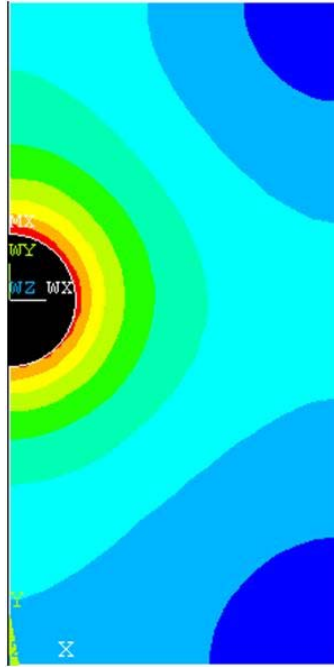


Figure 6 magnetic flux density distribution

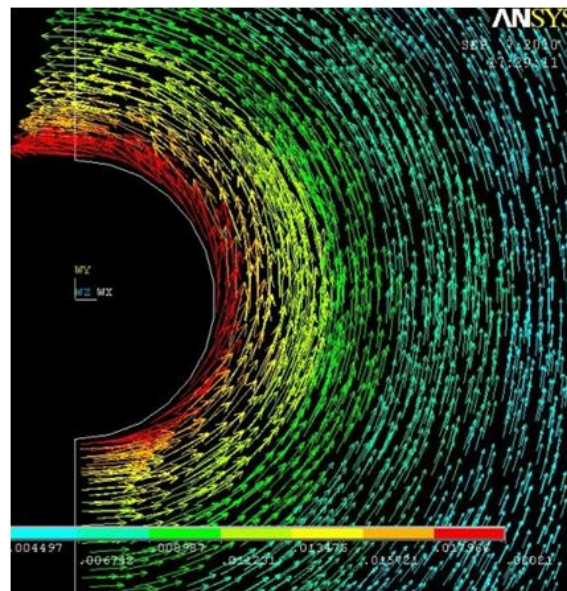


Figure 7 Magnetic flux trajectories

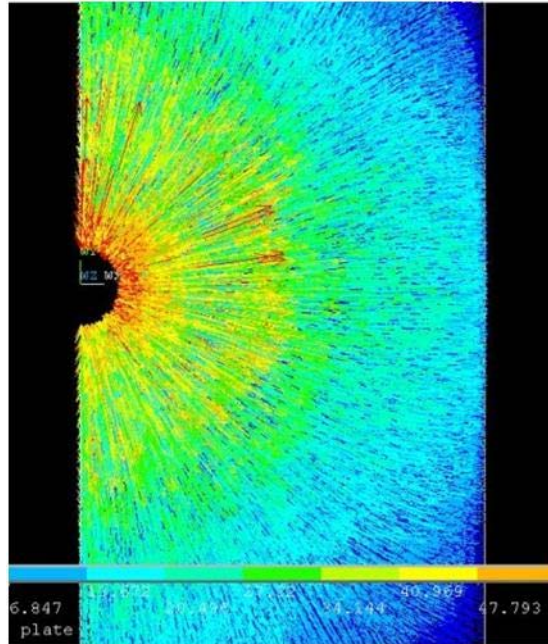


Figure 8 Eddy currents XY-projection, wire is z-directed

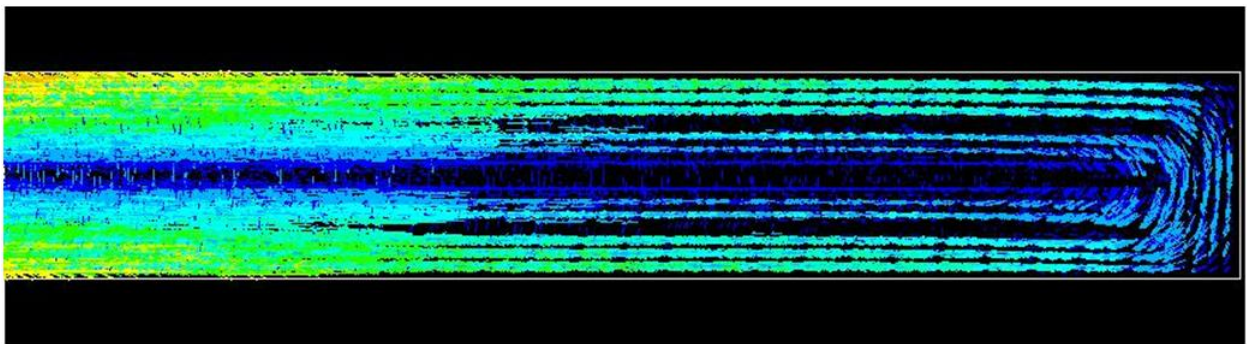


Figure 9 Eddy currents XZ projection, wire is z-directed

For thermal analyzes the cooling system was simulated by setting temperature of three plate's borders to 22 C. The characteristic thermo distribution is shown on Figure 10.

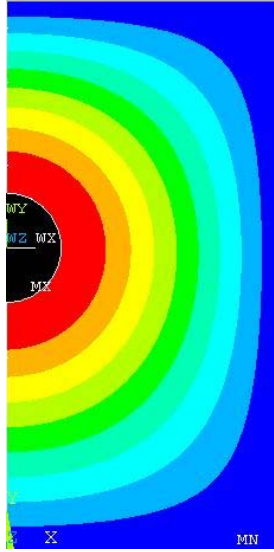


Figure 10 Temperature distribution

Results comparison

Magnetic field and temperature distribution were simulated for MnZn and NiZn ferrite plates on different currents. Material properties that were used for MnZn and NiZn ferrite plates' simulation are shown in Table 1. Magnetic permeability of materials was set constant, so BH-curve was not simulated and temperature dependency was ignored.

| Material Properties | MnZn | NiZn |
|--------------------------------------|------|------|
| <i>Permeability</i> | 6500 | 625 |
| <i>Volume Resistivity, ohm*m</i> | 500 | 1e8 |
| <i>Thermal conductivity, W/(m*C)</i> | 4 | 4 |

Table 1. Material Properties

Table 2 shows the results of flux, BH-losses and temperature data comparison. Experimental data set was compared with simulated for MnZn ferrite plate operated by 300 kHz alternating current. Simulated electromagnetic results are compared with initial experimental values. Simulated temperature distribution was compared with final experimental data set.

In experimental data analyzing magnetic flux is calculated using Faraday's law of induction for pick-up

coil. Simulated value was calculated using the following formulation: $F = \sum_i x_i * B_i * l$, where F – is magnetic flux, B_i – middle magnetic flux density value in zone, x_i – zone size, l – plate thickness.

Magnetic flux density simulation results (Figure 6) are used to get discrete values. Experimental and simulation flux value comparison shows that the discrepancy is less than 15%.

Experimental BH-loss value corresponds to sum of hysteresis and eddy-current heat loss. Simulation value is only eddy current loss. Value comparison shows that for MnZn ferrite material more than 50% of energy is loosed by eddy currents. In fact, MnZn material is supposed to have even more loss on eddy-currents.

T_{max} value corresponds to the closest to the wire RTD's value. Temperature comparison shows that model predicts higher heating of plate surface then experiment shows. The reason of discrepancy is studied in "Methodology" section.

| MnZn 300kHz | Current(A) | Beff(Gauss) | Flux,(Wb) | BH-loses(W) | T max(C) |
|--------------------|------------|-------------|-----------|-------------|----------|
| <i>Experiment</i> | 2.80 | 370.00 | 2.15E-05 | 46.00 | 65.00 |
| <i>Simulation</i> | | | 1.84E-05 | 29.40 | 104.00 |
| <i>Experiment</i> | 1.72 | 243.00 | 1.41E-05 | 18.50 | 39.00 |
| <i>Simulation</i> | | | 1.13E-05 | 11.14 | 53.00 |
| <i>Experiment</i> | 1.17 | 154.18 | 8.97E-06 | 8.40 | 29.00 |
| <i>Simulation</i> | | | 7.68E-06 | 5.17 | 36.50 |

Table 2. Experiment-simulation comparison for MnZn

Table 3 shows the same comparison for NiZn ferrite plate for different currents operating on 5.1 MHz. NiZn ferrite material, in contrast to MnZn ferrite is almost dielectric. It has lower eddy current loss and higher hysteresis loss. Hysteresis loss was not simulated, but simulation confirmed that eddy current loss is negligible small. Significant value of flux discrepancy needs additional investigation. The temperature distribution can't be simulated due to the fact that the predominant hysteresis loss is not considered in model.

| NiZn 5.1MHz | CurrentI(A) | Beff(Gauss) | Flux (Wb) | BH-loses(W) |
|--------------------|-------------|-------------|-----------|-------------|
| Experiment | 25.36 | 14.52 | 1.31E-06 | 300.00 |
| Simulation | | | 1.60E-05 | 1.62E-04 |
| Experiment | 15.84 | 11.48 | 1.04E-06 | 164.87 |
| Simulation | | | 9.98E-06 | 6.30E-05 |
| Experiment | 12.69 | 10.65 | 9.66E-07 | 112.39 |
| Simulation | | | 8.00E-06 | 4.05E-05 |
| Experiment | 9.54 | 9.60 | 8.60E-07 | 69.81 |
| Simulation | | | 6.05E-06 | 2.30E-05 |
| Experiment | 3.36 | 4.95 | 4.49E-07 | 8.65 |
| Simulation | | | 2.12E-06 | 2.84E-06 |

Table 3. Experiment-simulation comparison for NiZn

Diagram 1 shows the temperature dependency from distance for MnZn ferrite plate 300kHz 2.8A experiment. Blue plot shows the temperature values of five detectors set in line on the ferrite plate surface. Red plot shows the simulation values. Both experimental and simulation results show that temperature decreases almost linearly with distance.

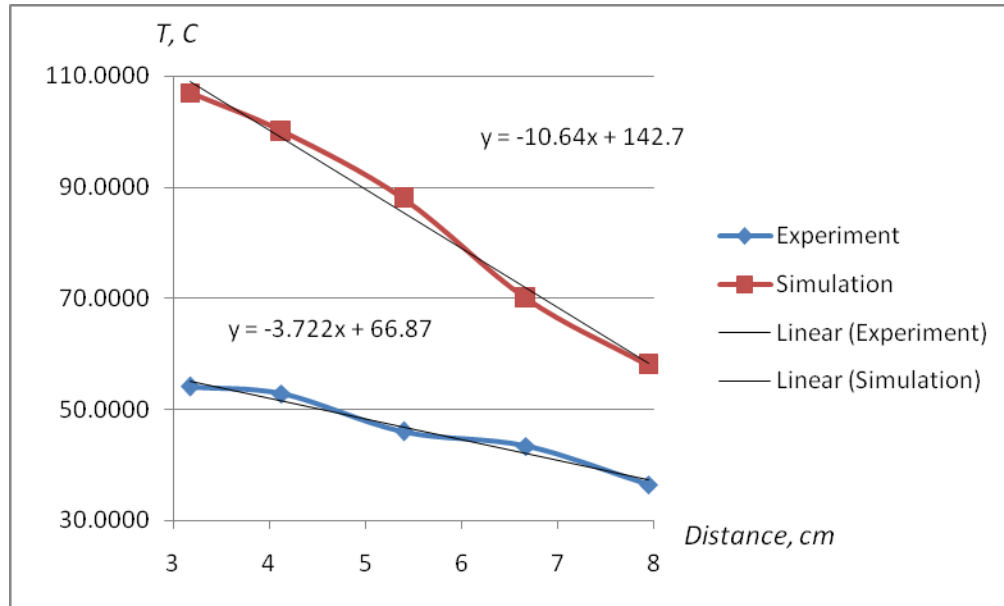


Diagram 1 Temperature dependency from distance for five RTDs.

Improvements

Obviously, the simulation model needs improvements:

1. Geometry. Cooling system has to be added to the model: Al volume in top and copper channel around the three sides of ferrite plate. Influences of these parts on EMF measurements are negligible small due to the fact that their relative permeability is almost one and they are far from excitation source. Nevertheless, these parts have significant influence on heat dissipation intensity.
2. Excitation. Linear wire is used in model to simulate the induction coil. The effect of these geometry difference is supposed to be negligible due to the presumption that magnetic field that is created in perpendicular to the plate direction is cancelled because of coil symmetry. More important is that in experiments voltage source is used, so current can vary, while in simulation current is constant. This effect is one of the reason, we can't simulate process in time and perform stable calculation.
3. Materials. Material properties differences have significant effect on simulation reliability. First of all, nonlinearity of BH-curve is not considered in simulation. Moreover, material properties: volume resistivity, permeability - are set independent from temperature. The first simplification is possible for MnZn EMF calculations, because this material has high eddy-current loss. But it can't be used for NiZn energy loss calculations. The second simplification is another reason process can't be simulated

in time. So simulation results are compared with initial experimental data set, when materials have well-known physical properties.

4. Heat dissipation. The experiment-simulation comparison has shown that heat dissipation system is not simulated properly. Radiation, air convection, dissipation in Al volume has to be taken in account to get better results.

Summarizing all, we suggest that material properties have to be set more accurately to improve electro-magnetic calculations. Several other heat dissipation mechanisms should be taken in account to improve temperature distribution simulations.

References

- [1] Mu2e Collaboration, "Proposal to search for $\mu\text{-N} \rightarrow \text{e-N}$ with a single event sensitivity below 10^{-16} ," FERMILAB-PROPOSAL-0973, Oct. 2008.
- [2] E.J. Prebys et al., "Extinction Magnet Specifications for the Mu2e Experiment" April 2, 2010

Appendix

1. P:\bulushev\article_bulushev\sources\plate2.txt – ANSYS source code for simulating magnetic flux and temperature distribution for one plate geometry
2. P:\bulushev\article_bulushev\sources\plate3.txt – ANSYS source code for simulating magnetic flux and temperature distribution for two plate geometry
3. P:\bulushev\article_bulushev\Simulation.pptx – final presentation